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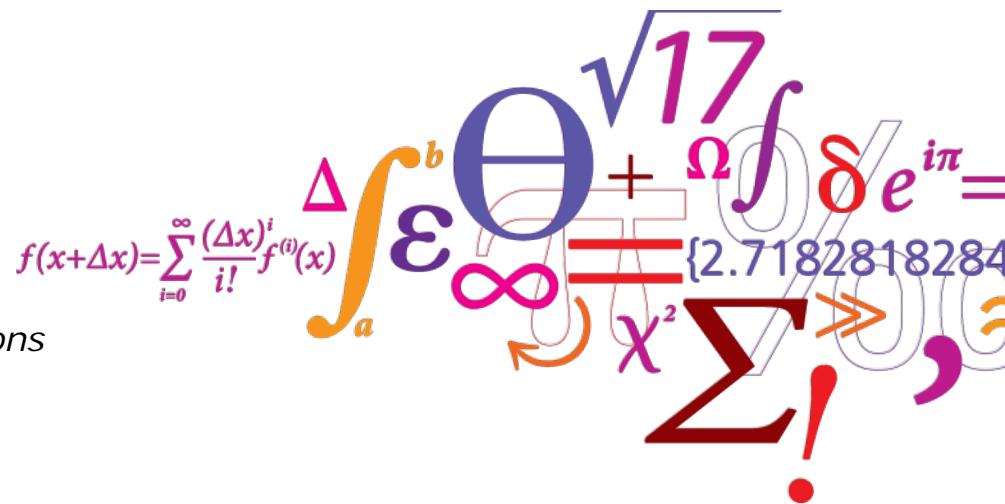
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A Model Based Control methodology combining Blade Pitch and Adaptive Trailing Edge Flaps in a common framework

Lars Christian Henriksen, DTU Wind Energy
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 Peter Bjørn Andersen, DTU Wind Energy



Aeroelastics: next level challenges and solutions

EWEA Wind Energy Conference,
Vienna, 4-7 February 2013

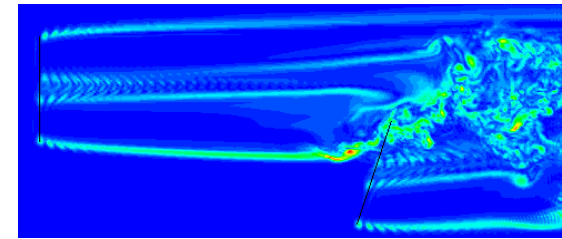
Structure of the presentation

- Introduction
 - Why Smart Rotors? Why a combined control framework?
- Model Based Control Framework
 - Problem formulation
 - Aerodynamic and structural models
 - Verification: compare response on the structure
- Simulation Test Case
- Applications and results
 - Focus on Blade Root Loads Alleviation
- Other applications (preliminary):
 - Increase power capture?
- Conclusion and Future Work

Introduction

Why Smart Rotors?

- Wind turbine operate in non uniform wind field
- What is a smart rotor?
 - Combination of sensors, control unit, actuators
 - Actively reduces the loads it has to withstand
 - Actuators:
 - Blade Pitch
 - Distributed aerodynamic control (Trailing Edge Flaps)
- Literature: simulation and a few experiments
 - Different configurations & conditions
 - Widespread figures (from 5 % to 45 %)
 - All confirm load alleviation
- Active load alleviation
 - Road to up-scaling?
 - Road to decreased Cost of Energy?
 - Next level challenge/solution?



Introduction

Why a combined control framework?

- Traditional smart rotor control approach:
 - ‘classic’ power regulation control unmodified
 - Superimposed control for load alleviation
 - Avoid interferences by frequency separation

Aim of the investigation:

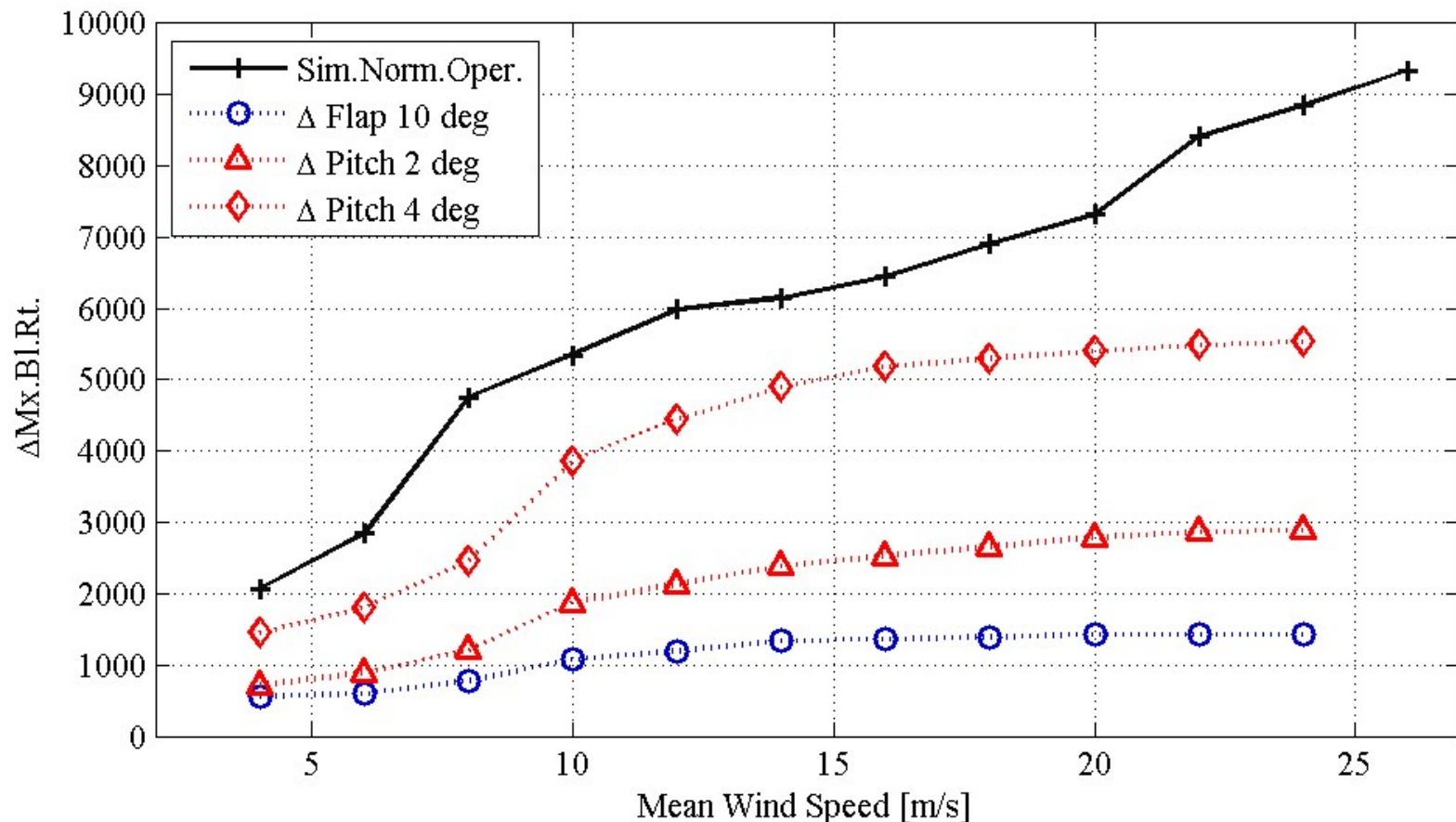
Outline a combined control framework, explore its possibility, and its advantages

- A single control system integrates generator, pitch, and distributed device control
- Main focus: Application to blade load alleviation
- Other application are possible:
 - Enhanced energy capture below rated conditions (preliminary)
 - Drive train and generator load alleviation
 - ...

Introduction

Why a combined control framework?

- “In union there is strength”...
- Load variation in IEC conditions compared to actuator variation



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How: Model Based Control framework

- Formulated as Model Predictive Control problem:

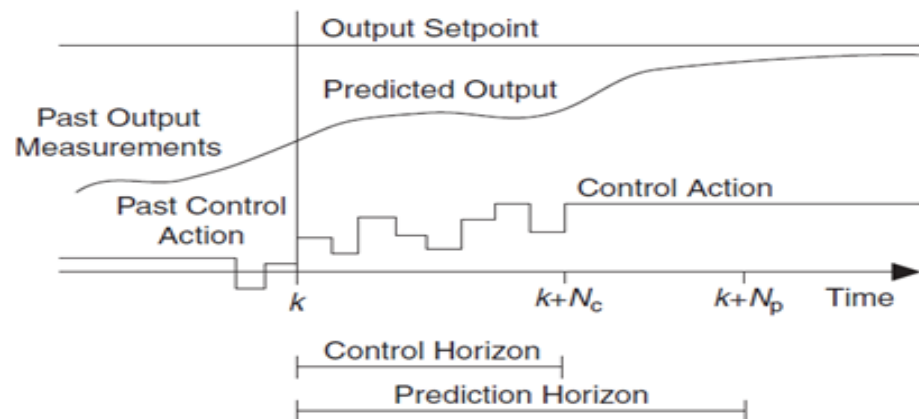
- **Optimal control:**

Minimizes objective function: $J = f(\bar{x}, \bar{u}, \bar{w})$
 s.t. a set of constraints

- **Model Based control:**

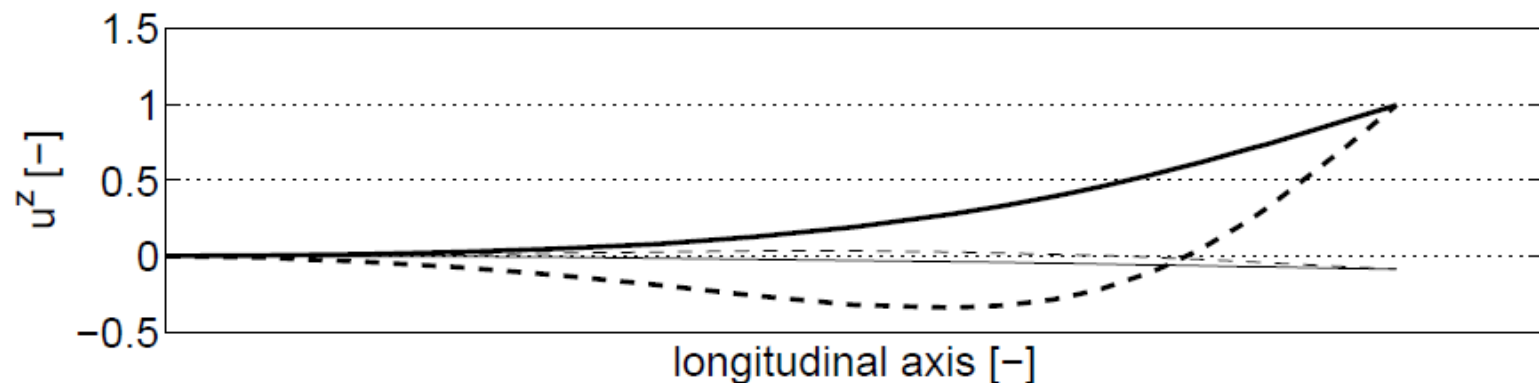
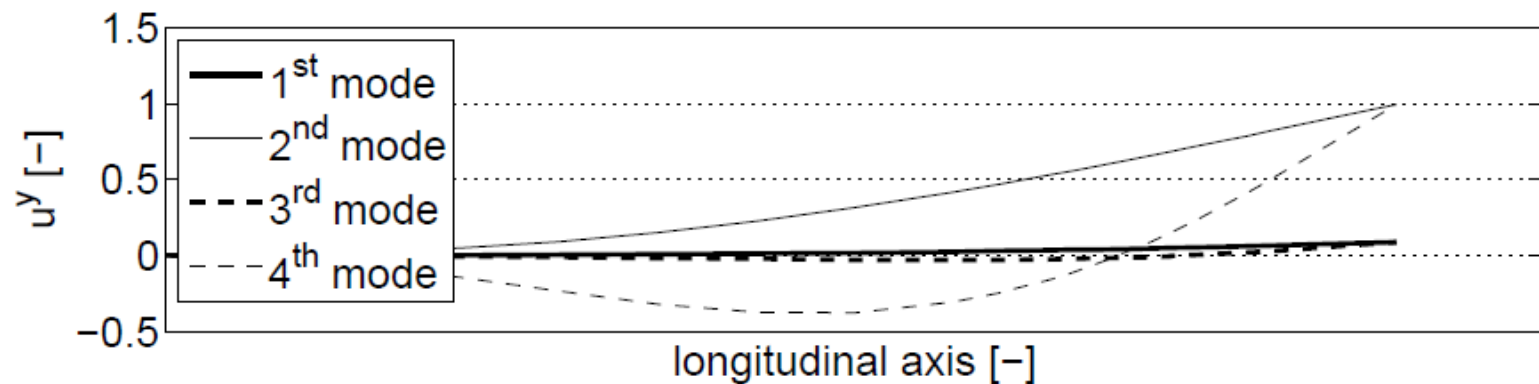
Control design requires a model of the system to control

- Linear model
- Capture relevant dynamics \Leftrightarrow simple model
- Aeroelastic problem: model structure & aerodynamics
- (First principle model)



Structural model (in MPC)

- Modal shape function approach (simplified model):
 - Superposition of deflection shape functions → Component deflection
 - Deflection shape → Eigenmodes
 - Tower 1 FA + 1SS, Drive Train 1 Torsion
 - Blade: 2 Mx + 2 My



Aerodynamic model (in MPC)

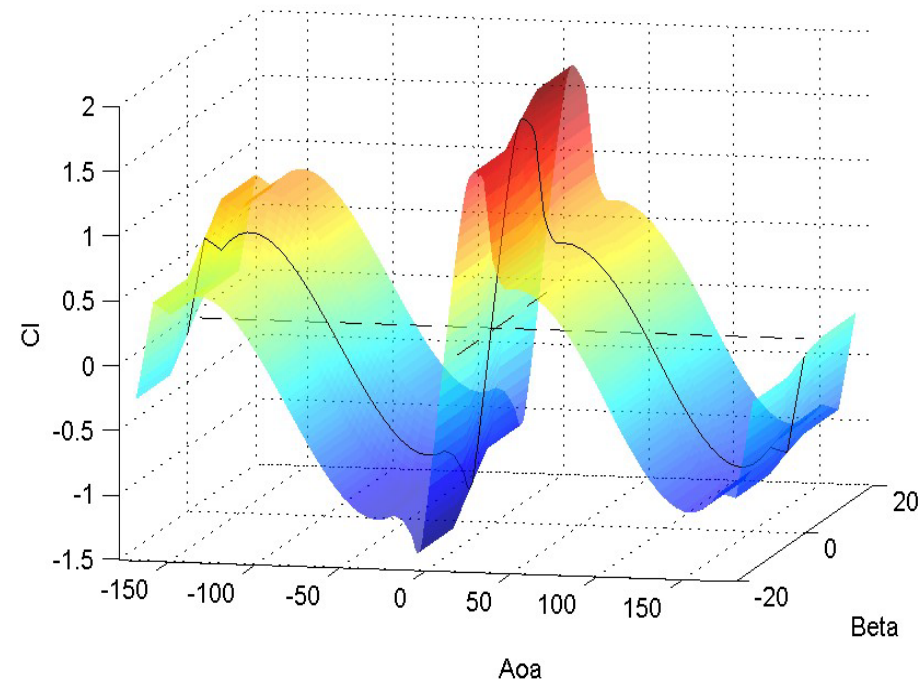
- Linearized BEM-based formulation:
 - Compute a-priori (quasi-steady lookup):
 - Integral aerodynamic forces $C_l(\alpha, \beta)$
 - Induction velocities $a(\theta, \lambda, \beta)$
 - Linearized dependence on flap
 - Dynamic inflow as 1st order filter

Lift and drag

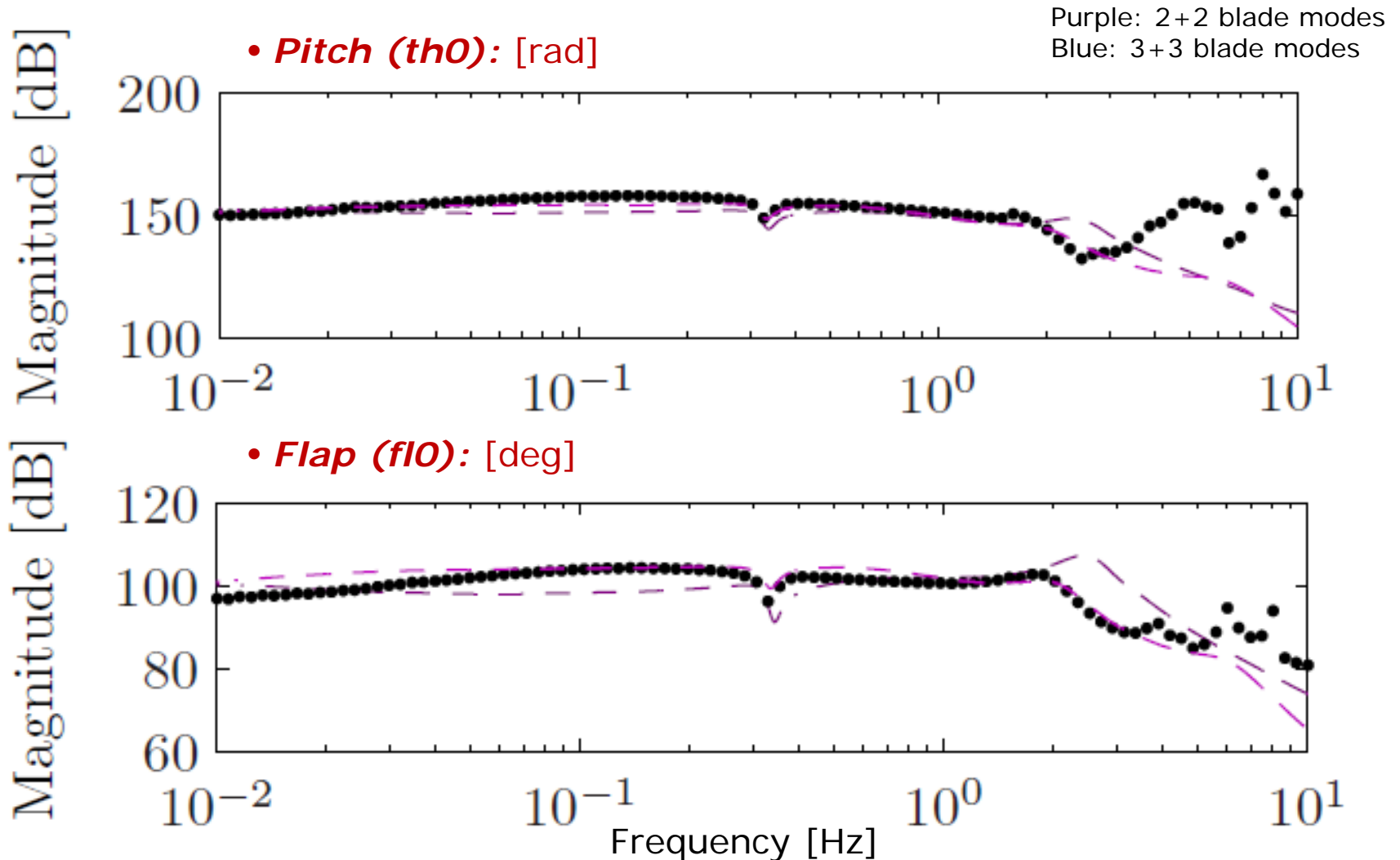
- $L = \frac{1}{2} \rho W^2 C_L(\alpha, \beta) \approx \frac{1}{2} \rho W^2 C_L(\alpha, 0) + \frac{1}{2} \rho W^2 \frac{\partial C_L(\alpha, 0)}{\partial \beta} \beta$
- $D = \frac{1}{2} \rho W^2 C_D(\alpha, \beta) \approx \frac{1}{2} \rho W^2 C_D(\alpha, 0) + \frac{1}{2} \rho W^2 \frac{\partial C_D(\alpha, 0)}{\partial \beta} \beta$

Induction factors normal and tangential to the rotor plane

- $a(\theta, \lambda, \beta) \approx a(\theta, \lambda, 0) + \frac{\partial a(\theta, \lambda, 0)}{\partial \beta} \beta$
- $a'(\theta, \lambda, \beta) \approx a'(\theta, \lambda, 0) + \frac{\partial a'(\theta, \lambda, 0)}{\partial \beta} \beta$



Verification: Response on blade root



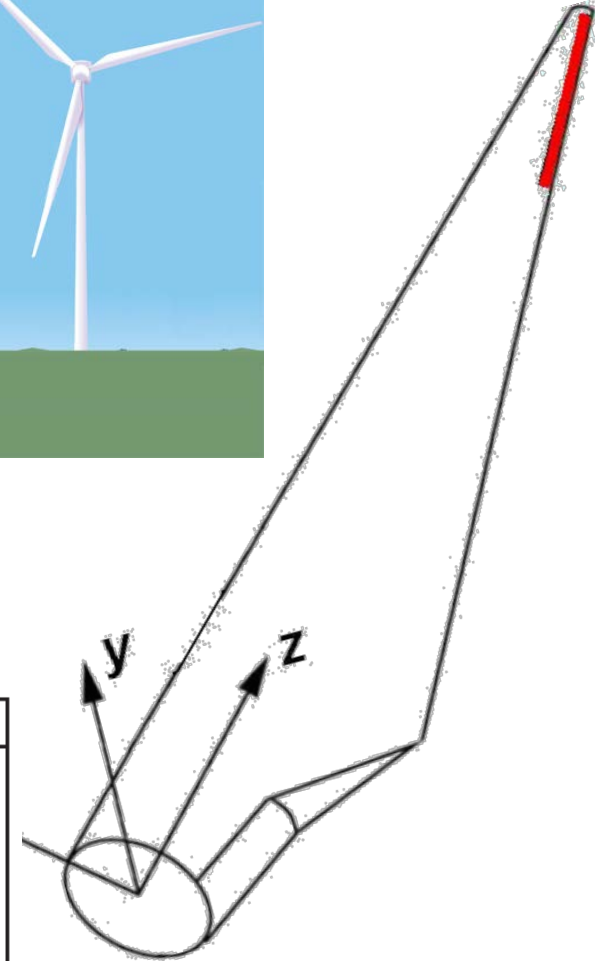
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Simulation Test Case

Simulation Test Case

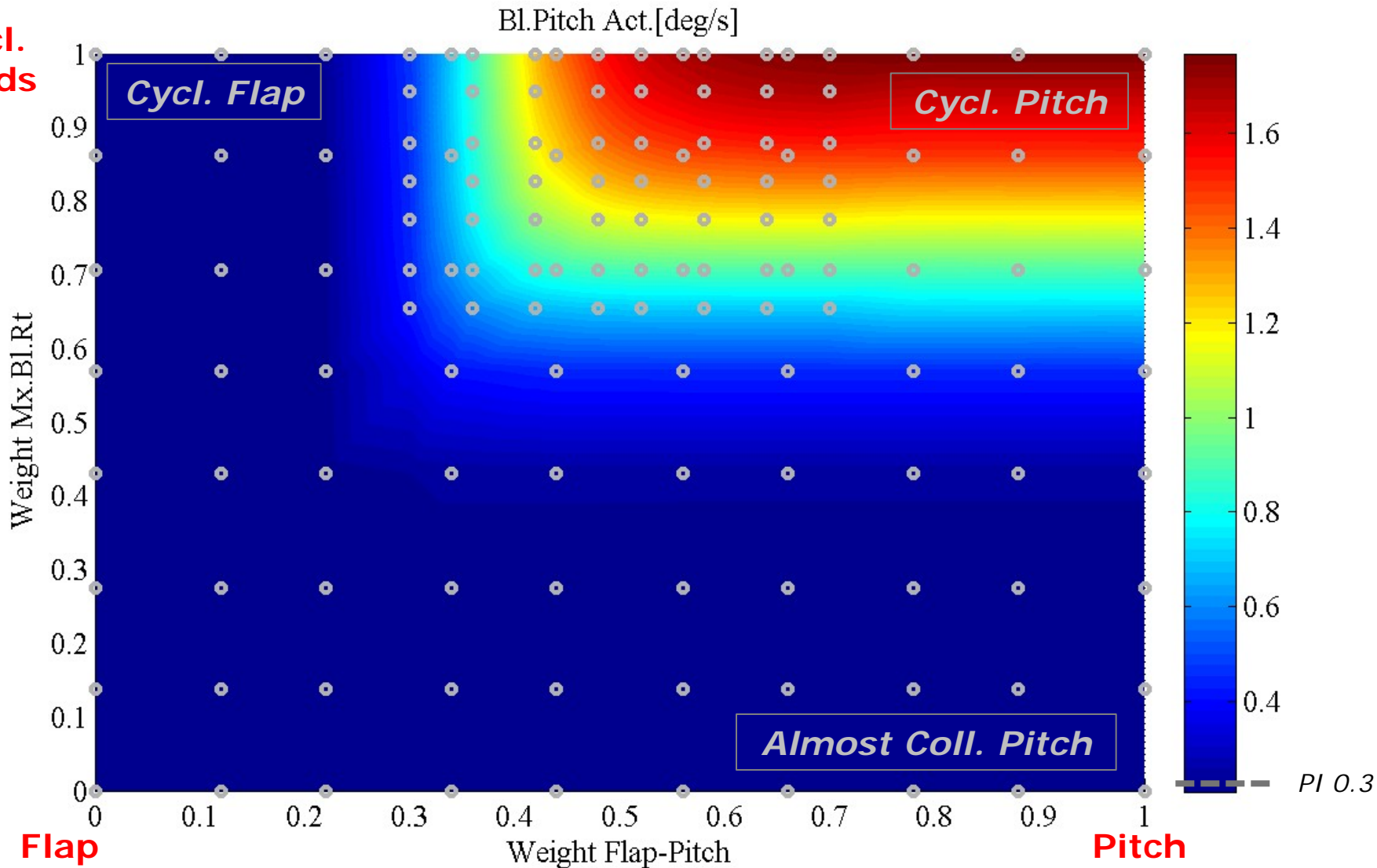
- Reference NREL 5 MW turbine
- Adaptive Trailing Edge Flaps
 - All flaps on one blade moved as one
- Sensors:
 - Shaft sp., Blade root b.mom, Tower top acc.
- Simulations with HAWC2
 - Multibody dynamics, includes torsion
 - Unsteady BEM aerodynamics
- IEC conditions: class A. Iref: 0.16 (wsp: 18 m/s)
- Focus on blade load alleviation



Reference Wind Turbine		Flap Setup	
Rat. Power	5 MW	Chordwise ext.	10%
Num. Blades	3	Deflect. limits	$\pm 10^\circ$
Rotor Diam.	126 m	Max. ΔCl	$-0.45 \sim +0.41$
Blade length	61.5 m	Spanwise length	12.3 m (20% blade length)
Rat. Rot. Sp.	1.267 rad/s	Spanwise loc.	from 47.7 m to 60.0 m span
Hub height	90 m	Max. $\Delta M_{x, Bl. Rt}$	approx. ± 1100 kNm

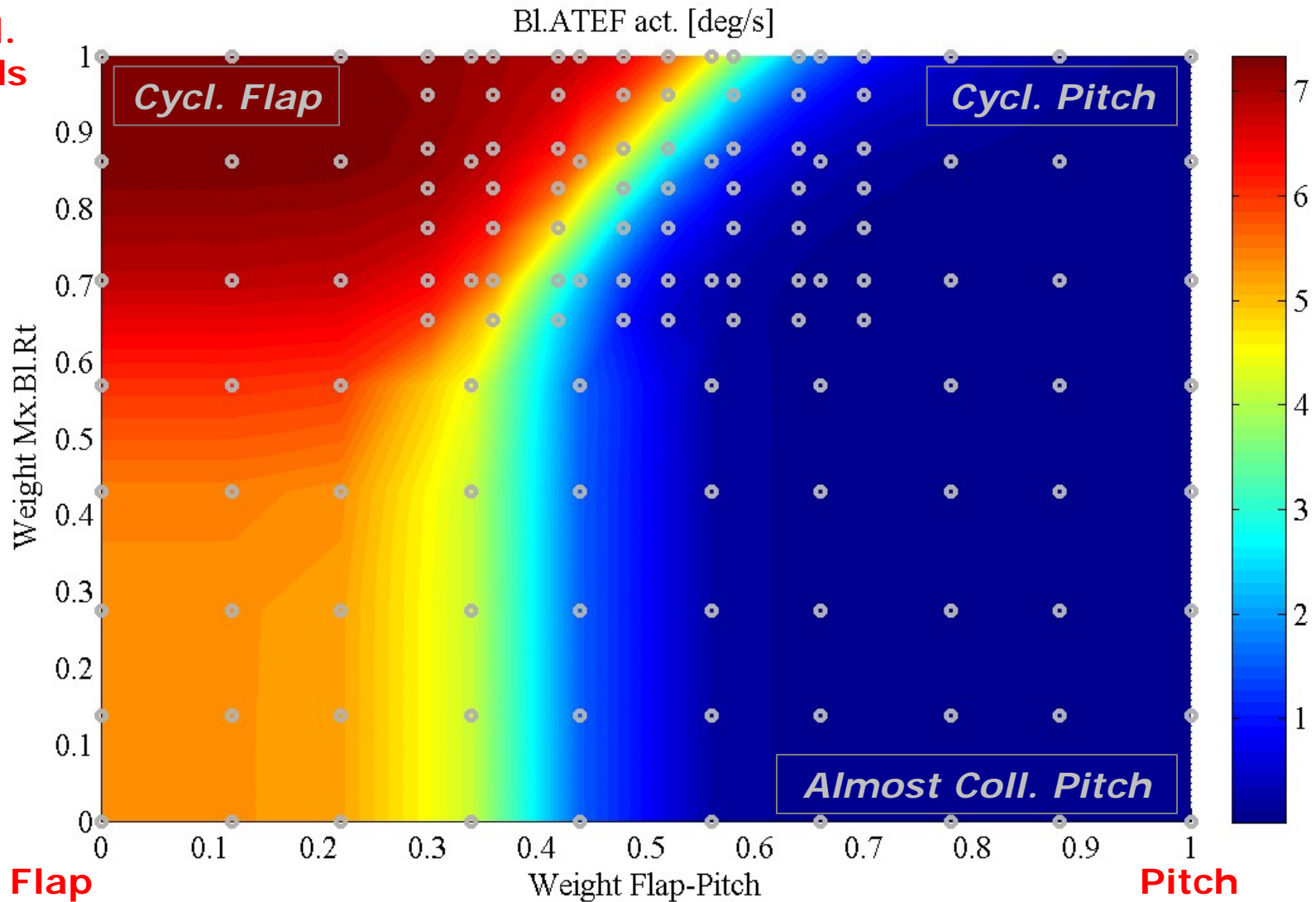
Blade Root Loads Alleviation

Cycl.
Loads



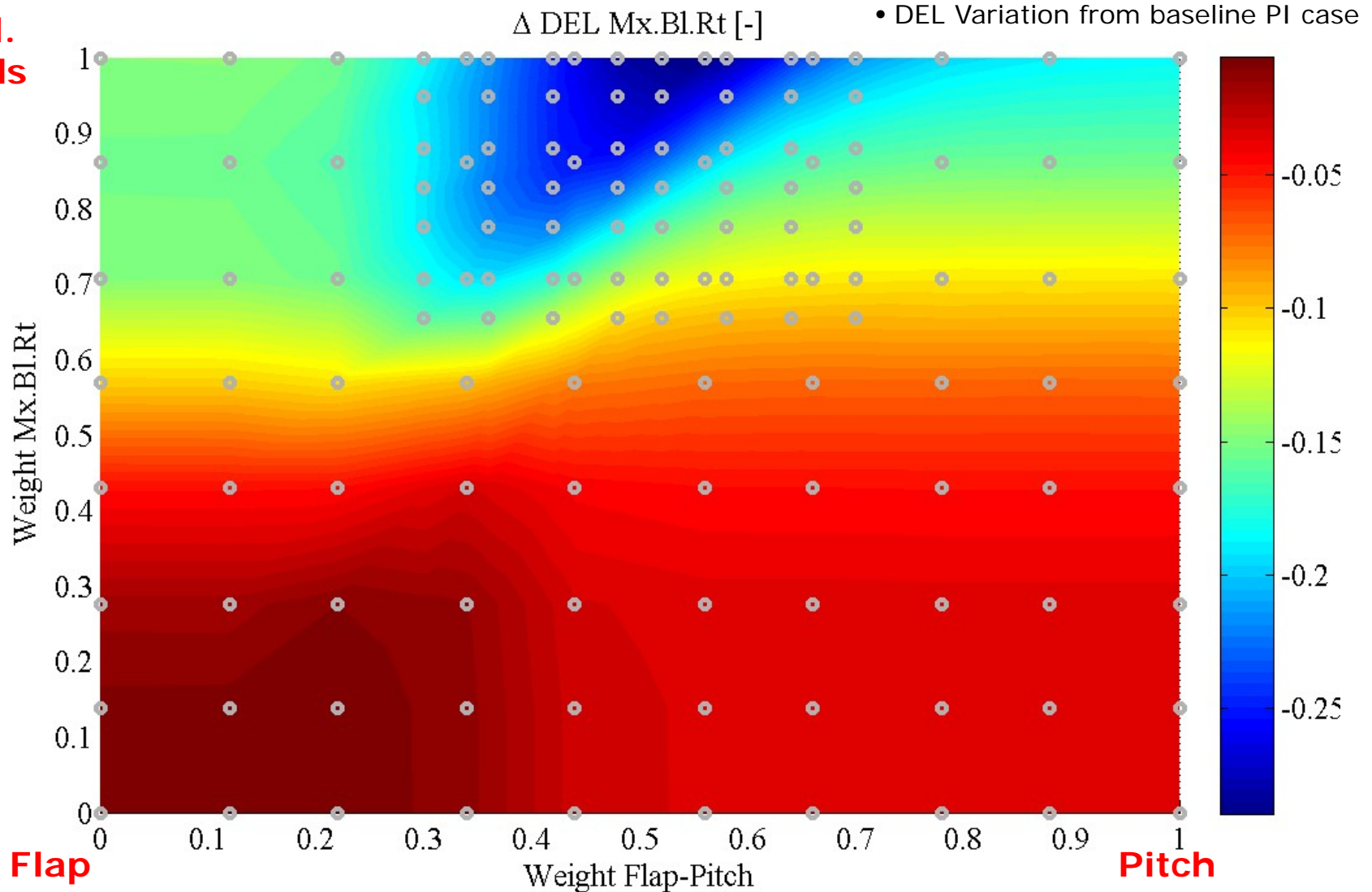
Blade Root Loads Alleviation

**Cycl.
Loads**



Blade Root Loads Alleviation

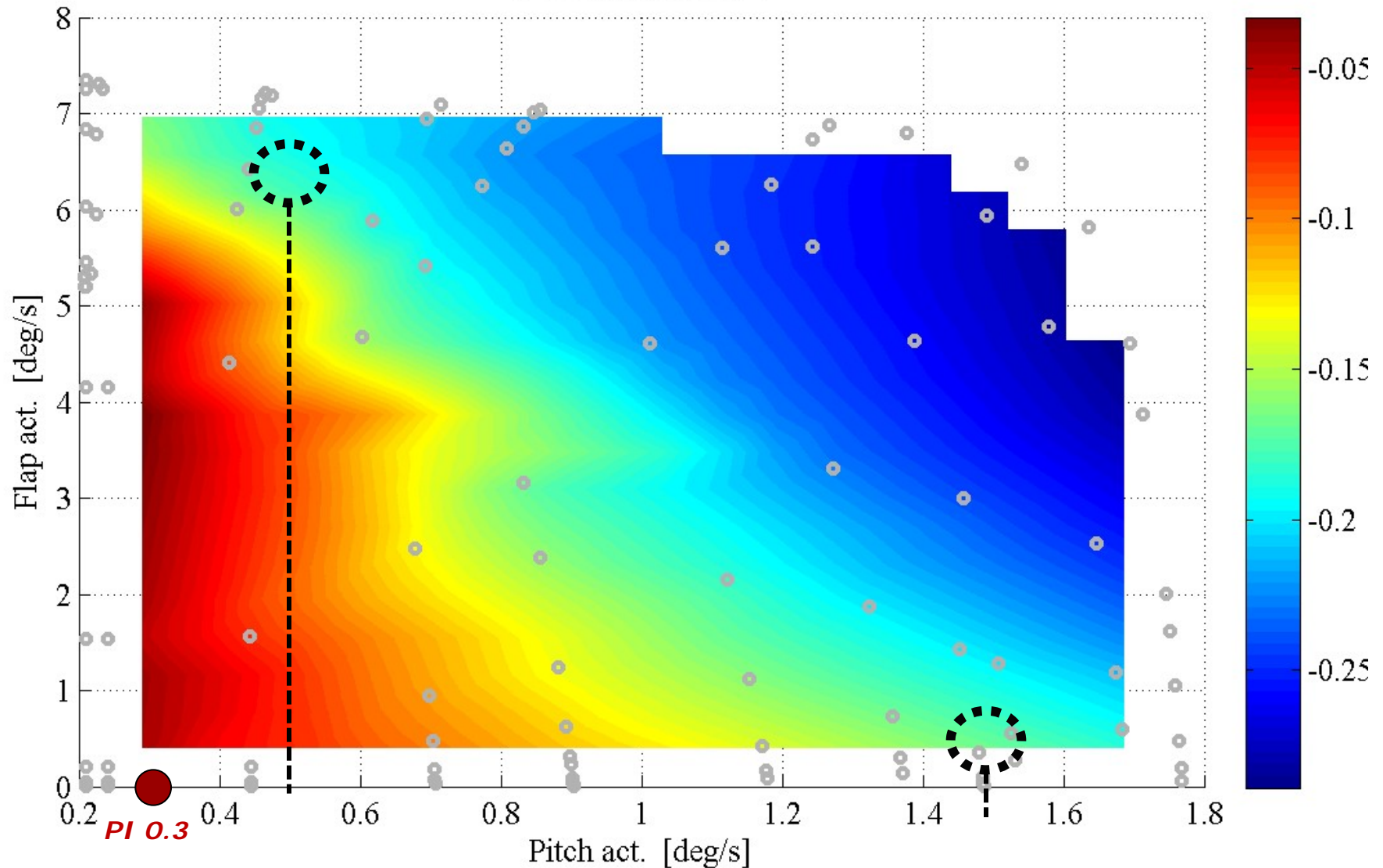
**Cycl.
Loads**



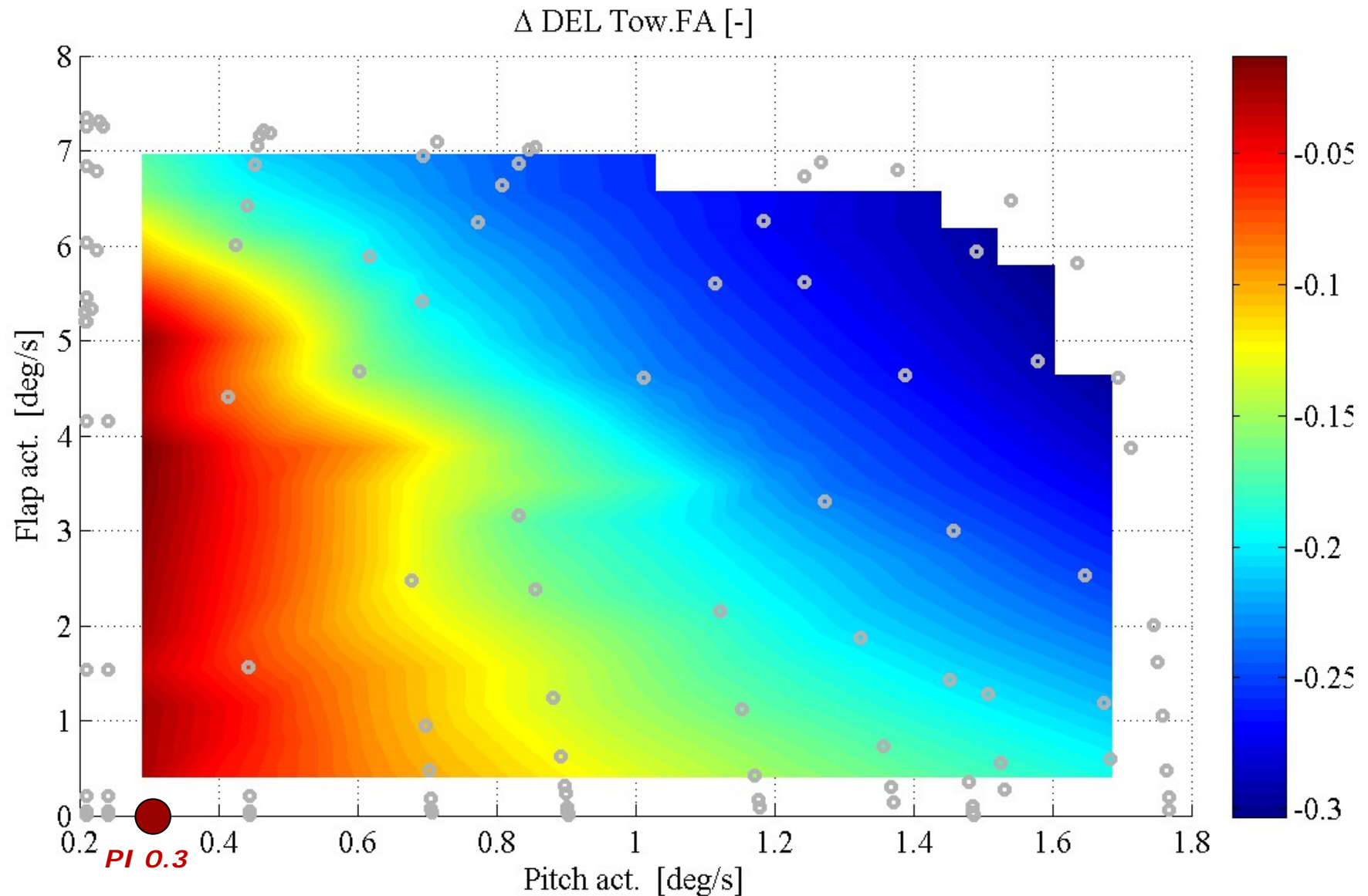
Application and results

Blade Root Loads: "cost-benefit"

$\Delta \text{DEL Mx.Bl.Rt [-]}$



Effects on tower



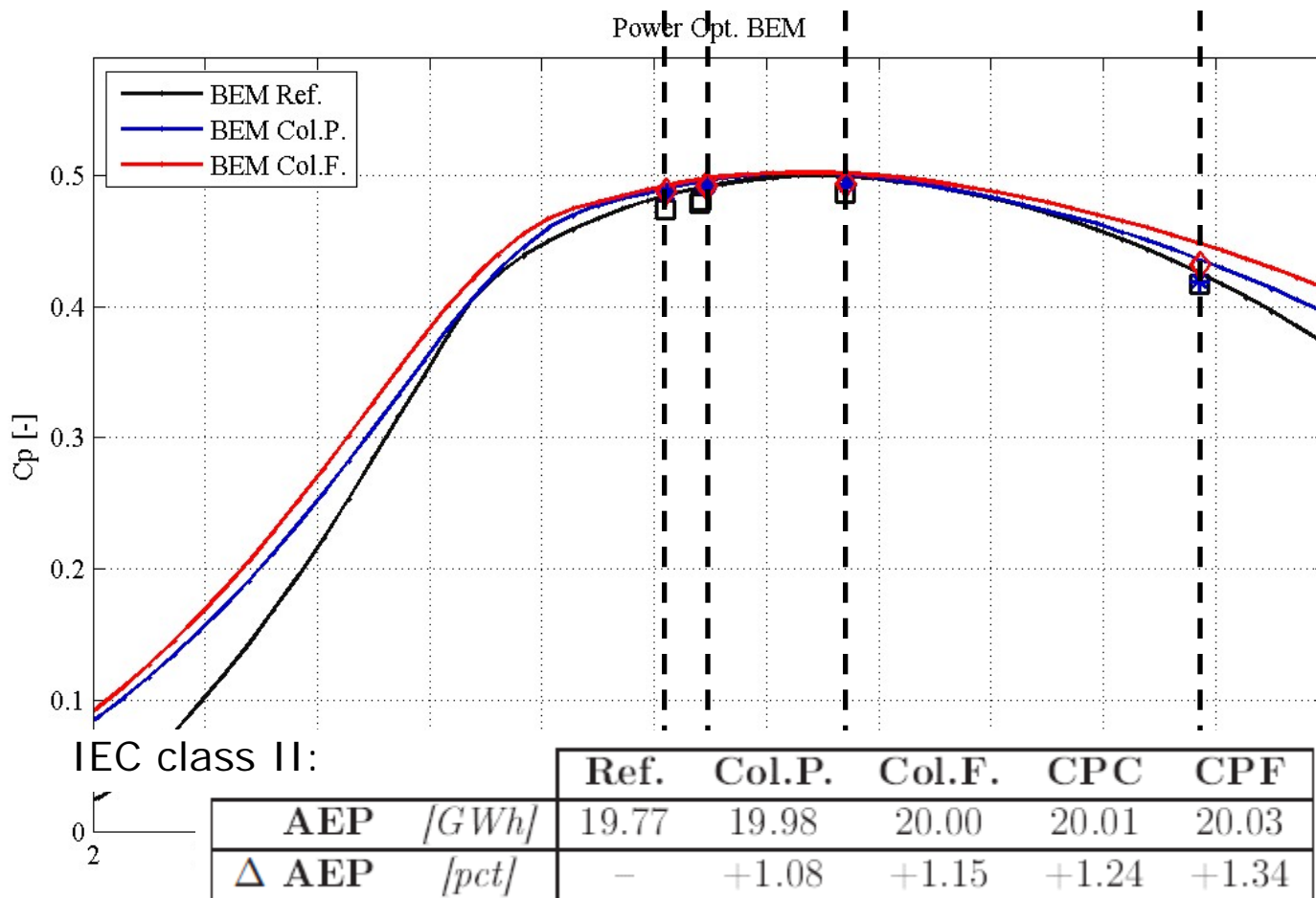
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Other Applications: Increase power capture (concept)

Increase power capture below rated

- Below rated: load alleviation not convenient
- Use Adaptive Trailing Edge Flaps to increase power capture?
- Simple BEM analysis (ideal rigid rotor):



- No gain at optimal Cp-Lambda

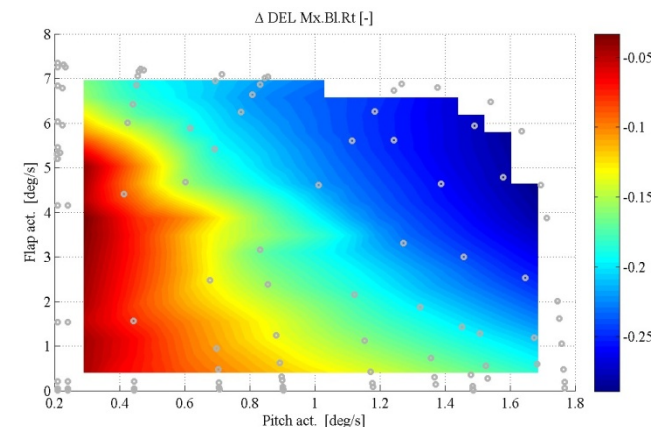
Quick-check with std. controller:

- Sub-optimal operational pts
- Tower frq.

- Variations around an operational point

Conclusion

- “In union there is strength” applies to Smart Rotors
- MPC framework:
 - Positive collaboration of pitch and flap actuators
- Advantages of combined actions: load alleviation
 - Increase alleviation potential: [15 %; 18 %] → 30%
 - Spare pitch, take over with flap (or viceversa): 16 % + fl → 1/3
 - Alleviation on other parts of the structure
- Possibly enable other applications (future work)
 - Distributed actuators and sensors
 - Enhance power capture
 - Reducing loads in DT and speed variation
 - ...



Thank you...



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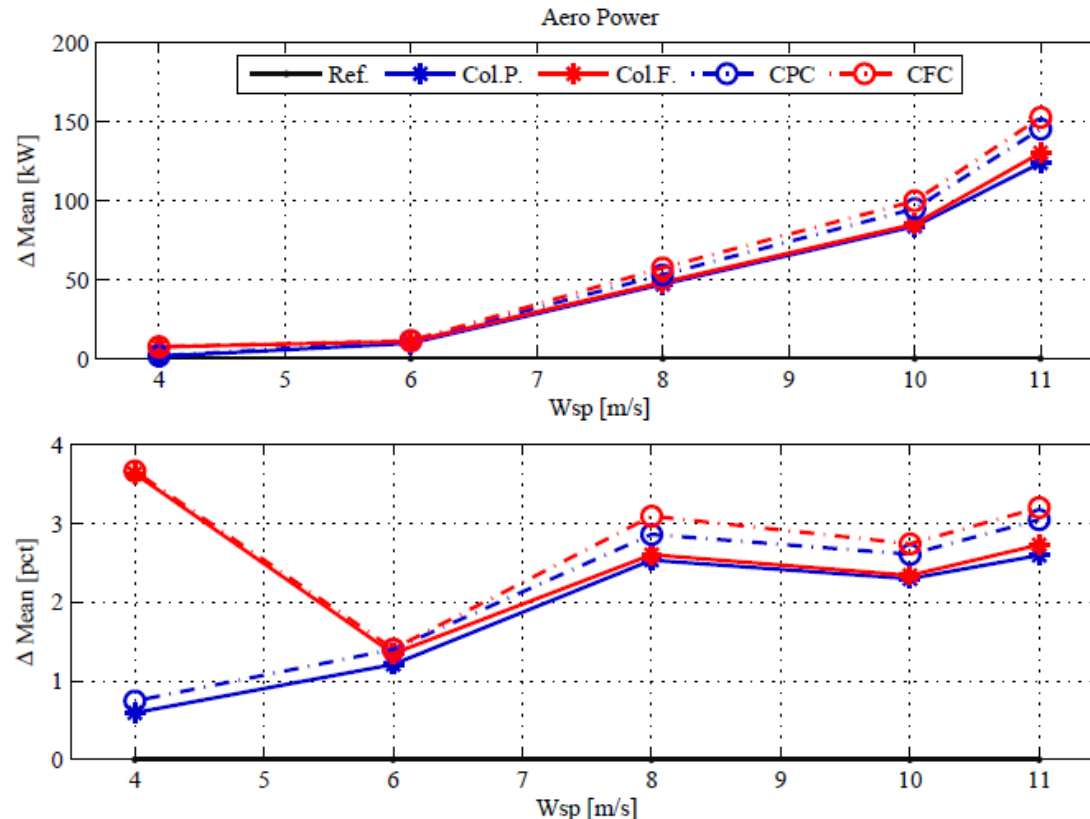
Bonus slides...

Other Applications: Increase power capture (concept)

Increase power: cyclic

- Simplified analysis: optimize power from cyclic flow variations
- Stiff rotor in deterministic (no turbulence) wind field

Results need to be confirmed in "realistic" conditions!



Cyclic trajectories for power increase load variation

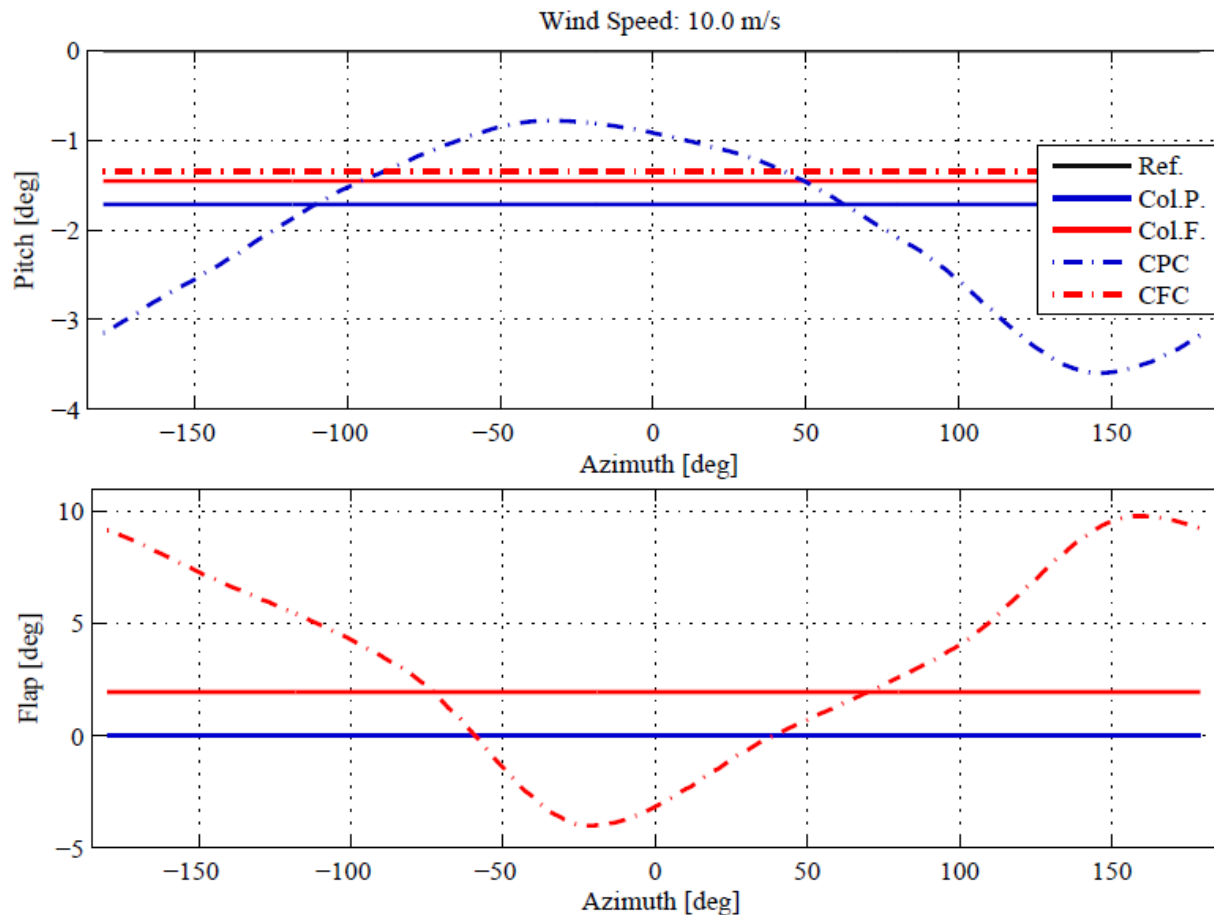
IEC class II:

	Ref.	Col.P.	Col.F.	CPC	CPF
AEP [GWh]	19.77	19.98	20.00	20.01	20.03
Δ AEP [pct]	—	+1.08	+1.15	+1.24	+1.34

Other Applications: Increase power capture (concept)

Increase power capture: cyclic trajectories

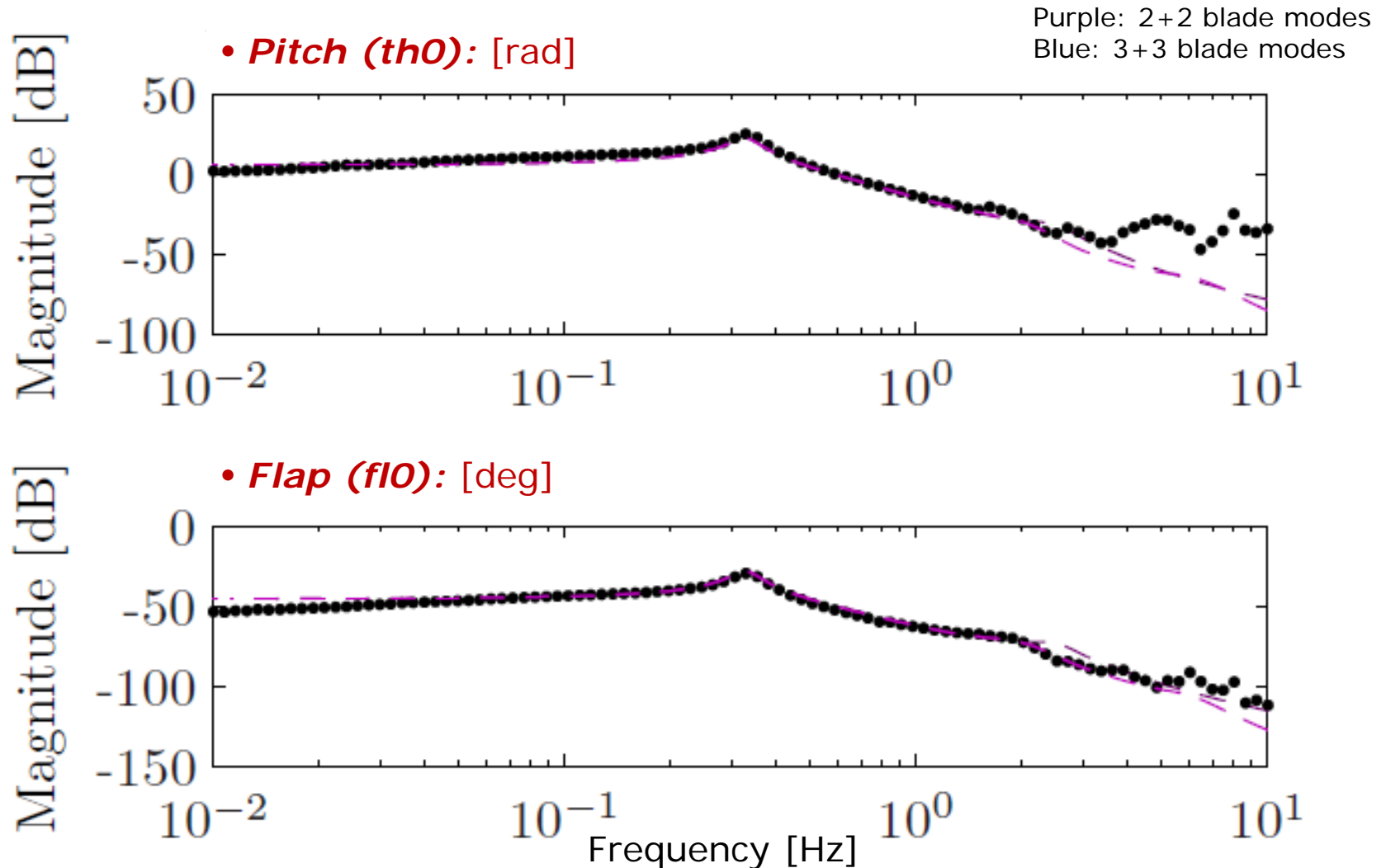
- Cyclic control action for increased power capture increases blade load variation



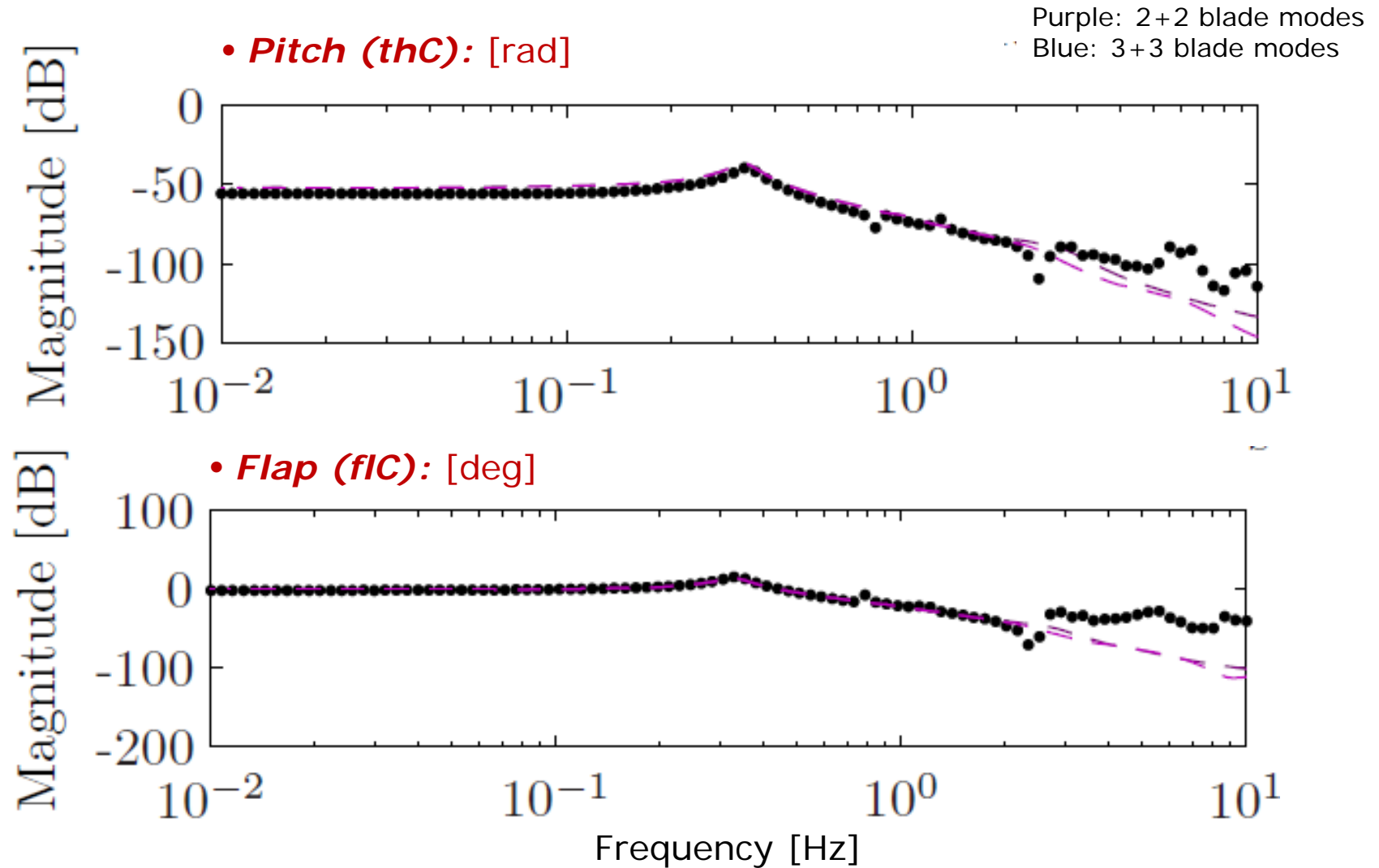
- As lambda increases, better C_p is in the direction of lower C_t

→ Amplifies load variation

Verification: Response on tower bottom



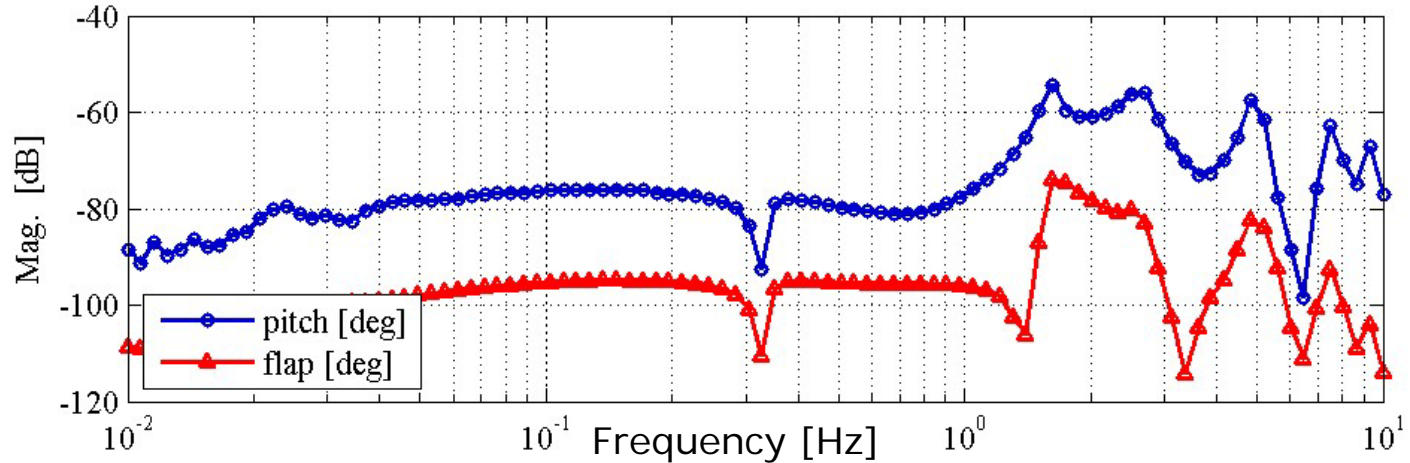
Verification: Response on tower bottom



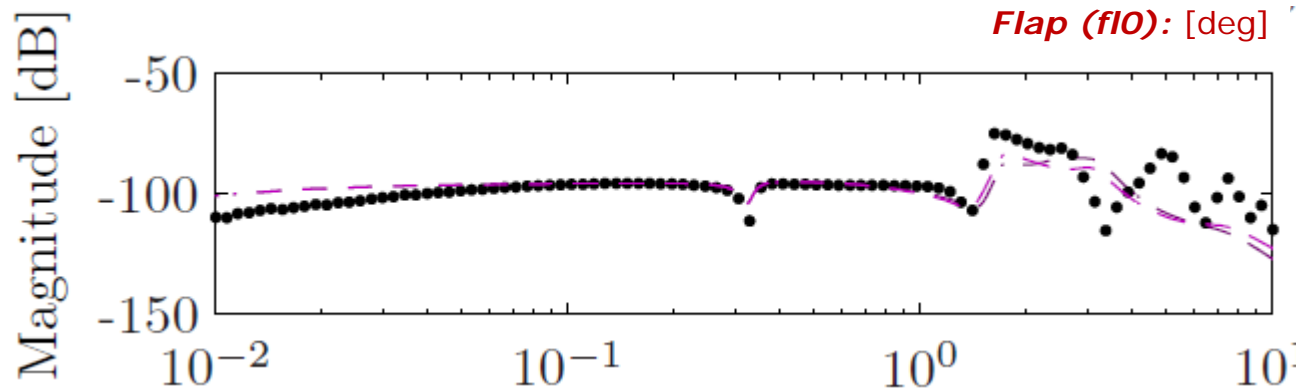
Other Applications: Drive train load alleviation

Drive train load alleviation (preliminary)

- Collective flap and pitch both have an effect on aero torque and shaft torsion



- Also modeled in the MPC framework:



- Use flap to help in reduction of torque fluctuations → reduce DT requirements